FE implementation of Fung elastic model for planar anisotropic biological materials

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Introduction: Accurate computational modeling of the non-linear, anisotropic mechanical properties of planar biological tissues remains an important and challenging area. Among various constitutive models developed, the exponential model proposed by Fung [1] is perhaps the most widely used one. Although in literature over several decades, the implementation of this model into finite element (FE) simulations has been very limited, especially in simulating complex shear behavior. The main reason is due to the high non-linearity of the model that leads to the numerical instability/convergence problems. To address this issue, we enforced the restrictions on the model necessary to achieve numerical stability. We utilized ABAQUS as a platform to implement the model. Numeric results were validated against theoretic solutions as well as actual experiment data.

Methods: It is assumed that planar biological materials behave hyperelastically and follow the concept of pesudoelasticity [1]. Thus the in-plane second Piola-Kirchhoff stresses $\mathbf{S}$ can be derived from strain energy function W through: $\mathbf{S} = \frac{\partial W}{\partial \mathbf{E}}$, where $\mathbf{E}$ is Green strain tensor. A general anisotropic Fung elastic model, incorporating the effects of in-plane shear,

$$W = \frac{c}{2}\left[e^{Q} - 1\right],\quad Q = A_1E_{11}^2 + A_2E_{22}^2 + 2A_3E_{11}E_{22} + A_4E_{12}^2 + 2A_5E_{12}E_{11} + 2A_6E_{12}E_{22}$$

was utilized to characterize the biaxial mechanical response of glutaraldehyde treated bovine pericardium (GLBP), a traditional biomaterial for prosthetic heart valves. Two restrictions were imposed on the model, 1) the strain energy function W needs to be convex; 2) condition number of material stiffness matrix needs to be lower than a prescribed value. These restrictions lead to a set of bounds that can be enforced in nonlinear regression for parameter estimates to form the model. The model was incorporated into ABAQUS through subroutine UMAT. Updated-Lagrangian formulation was used. 8-node biquadratic, reduced integration plane stress element (CPS8R) was used for all simulations.

Results: With the restrictions imposed on the model, in single element test for user-defined material an exact match between FE output and analytic solution, for both normal and shear components, was obtained. When compared with actual multi-protocol biaxial experiment data, excellent matches were obtained. Finally, we simulated a 400 elements load-controlled biaxial experiment and the stress distribution on the specimen was analyzed. These results indicate that in addition to physical plausibility, numeric constrains are required in constructing an experimentally driven hyperelastic model. The successful implementation of the Fung elastic model also suggests that accurate design and functional simulations using realistic non-linear anisotropic material models of biomaterials are both feasible and practical.

References: 1. Fung, Y.C., Biomechanics: Mechanical Properties of Living Tissues. 1993.
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